Recent results for tau LFV decays from Belle

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Introduction

Lepton flavor violation (LFV) in charged leptons
⇒ negligibly small probability in the Standard Model (SM)
even taking into account neutrino oscillations

$$Br(\tau \rightarrow \ell \gamma)_{SM} \propto \left( \frac{\delta m_{\nu}^2}{m_W^2} \right)^2 < 10^{-54}$$

(EPJC8 513 (1999))

Observation of LFV is a clear signature of New Physics (NP)
• Many extensions of the SM predict LFV decays.
⇒ These branching fractions could be enhanced as high as current experimental sensitivity.

Tau lepton:
- The heaviest charged lepton
- Many possible LFV decay modes
⇒ Ideal place to search for LFV
LFV in SUSY

SUSY is the most popular candidate for BSM among new physics models

naturally induce LFV at one-loop due to slepton mixing

\[ \tau \rightarrow \ell \gamma \] mode has the largest branching fraction in SUSY-Seesaw (or SUSY-GUT) models

When sleptons are much heavier than weak scale

LFV associated with a neutral Higgs boson (h/H/A)

Higgs coupling is proportional to mass \( \tau \)
\[ \Rightarrow \mu \mu \text{ or } s \bar{s} \] (\( \eta, \eta' \) and so on) are favored and \( \text{Br} \) is enhanced more than that of \( \tau \rightarrow \mu \gamma \).

To distinguish which model is favored, various searches for \( \tau \) LFV are important!
Belle completed data taking on Jun. 30, 2010. Total: >1 ab$^{-1}$

- Y(4S): 711 fb$^{-1}$
- Y(5S): 121 fb$^{-1}$
- Y(3S): 3.0 fb$^{-1}$
- Y(2S): 24 fb$^{-1}$
- Y(1S): 5.7 fb$^{-1}$

Off-resonance: 87 fb$^{-1}$

Integrated Luminosity (pb$^{-1}$)

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Y(4S)</th>
<th>Y(5S)</th>
<th>Y(3S)</th>
<th>Y(2S)</th>
<th>Y(1S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>711 fb$^{-1}$</td>
<td>121 fb$^{-1}$</td>
<td>3.0 fb$^{-1}$</td>
<td>24 fb$^{-1}$</td>
<td>5.7 fb$^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>87 fb$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\sigma(\tau\tau) \sim 0.9$ nb, $\sigma(b\bar{b}) \sim 1.1$ nb

A B-factory is also a $\tau$-factory!

Good track reconstruction and particle identification

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>mID</th>
<th>eID</th>
</tr>
</thead>
<tbody>
<tr>
<td>~85%</td>
<td>~90%</td>
<td></td>
</tr>
</tbody>
</table>

Fake rate

- ~3%
- ~0.1%

$\sim 9 \times 10^8 \tau\tau$ at Belle

World-largest data sample!
**Analysis method**

- $e^+e^- \rightarrow \tau^+\tau^-$
  - 1 prong + missing (tag side)
  - $\mu + \gamma$ (signal side)

**Signal extraction:** $M_{\mu\gamma} - \Delta E$ plane

$$M_{\mu\gamma} = \sqrt{(E_{\mu\gamma}^2 - p_{\mu\gamma}^2)}$$

$$\Delta E = E_{\mu\gamma}^{CM} - E_{\text{beam}}^{CM}$$

Blind analysis

$\Rightarrow$ Blind signal region

Estimate number of BG in the singal region using sideband data and MC

$\Rightarrow$ UL is evaluated by F&C method (POLE).

This size is decided by the resolution
**Signature of signal and background**

**signal**

- Only tag side has neutrino!

**μμ event**

- Both sides have no neutrino → total energy is equal to beam energy.

**SM ττ event**

- Both sides have neutrinos → missing helps us to reject this kind of BG's.

**q̅q̅ event**

- Both sides have many tracks and photons. → No. of photons decreases this kind of BG's.

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**seminar@LNF**
Feature of Analysis for $\tau \rightarrow \mu \gamma, \mu \eta, \mu \mu \mu$

Generally,
- $\gamma$ in signal decay: difficult to distinguish from ISR or fake $\gamma$, makes resolution worse than in all-charged modes.
- Lepton: good efficiency and low fake rate, good resolution.

<table>
<thead>
<tr>
<th>BG rejection</th>
<th>Mass resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu \gamma$</td>
<td>very hard</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \eta$</td>
<td>hard (but $\eta$ mass window helps)</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \mu \mu$</td>
<td>easy($\mu$ID x3)</td>
</tr>
</tbody>
</table>

Besides, since $\tau \rightarrow \mu \gamma$ has only 2 particles, less kinematical information than that for other decays

Here, we discuss only $\eta \rightarrow \gamma \gamma$ subdecay mode.

<table>
<thead>
<tr>
<th>Main BG</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu \gamma$</td>
<td>$ee \rightarrow \mu \mu + \gamma$, $\tau \rightarrow \mu \nu \nu + \gamma$, $\tau \rightarrow \pi \nu + \gamma$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \eta$</td>
<td>$ee \rightarrow \mu \mu + \gamma \gamma$, $\tau \rightarrow \mu \nu \nu + \gamma \gamma$, $\tau \rightarrow \pi \nu + \gamma \gamma$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \mu \mu$</td>
<td>$ee \rightarrow \mu \mu \mu, ee \mu \mu$</td>
</tr>
</tbody>
</table>

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**Search for $\tau \to \ell \ell \ell$**

Update analysis from $543\text{fb}^{-1} \to 782\text{fb}^{-1}$

Apply almost same event selection as previous analysis

We observe no events in signal region for all modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eff. (%)</th>
<th>$N_{\text{BG}}^{\text{EXP}}$</th>
<th>UL ($\times 10^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-e^+e^-$</td>
<td>6.0</td>
<td>0.21 ± 0.15</td>
<td>2.7</td>
</tr>
<tr>
<td>$\mu^-\mu^+\mu^-$</td>
<td>7.6</td>
<td>0.13 ± 0.06</td>
<td>2.1</td>
</tr>
<tr>
<td>$e^-\mu^+\mu^-$</td>
<td>6.1</td>
<td>0.10 ± 0.04</td>
<td>2.7</td>
</tr>
<tr>
<td>$\mu^-e^+e^-$</td>
<td>9.3</td>
<td>0.04 ± 0.04</td>
<td>1.8</td>
</tr>
<tr>
<td>$\mu^-e^+\mu^-$</td>
<td>10.1</td>
<td>0.02 ± 0.02</td>
<td>1.7</td>
</tr>
<tr>
<td>$e^-\mu^+e^-$</td>
<td>11.5</td>
<td>0.01 ± 0.01</td>
<td>1.5</td>
</tr>
</tbody>
</table>

→(1.3-1.6) times more stringent results than previous.

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Search for $\tau \rightarrow \ell P^0(=\pi^0, \eta, \eta')$

previous result
Data : 401 fb$^{-1}$ @ Belle, 339 fb$^{-1}$@BaBar
(PLB648,341(2007)) (PRL98,061803(2007))

• To obtain high detection efficiency,
  $\eta(\eta')$ is reconstructed from $\gamma\gamma(\rho^0\gamma)$ as well as $\pi\pi\pi^0(\pi\pi\eta)$.

$\mathcal{B}<(0.8-2.4) \times 10^{-7}$ at 90%CL

• New search with 901 fb$^{-1}$ data sample

• To obtain better resolution, $\eta(\eta')$-momentum is evaluated by $\eta(\eta')$-mass-constrained fit.

• Differently from the previous analysis, selection criteria are set mode by mode.
  ex.) previous common required $P_\ell^{CM}<4.5$GeV/c $\rightarrow P_\mu^{CM}/\sqrt{s} < 0.38$ for $\tau \rightarrow \mu \eta$
  new not required for $\tau \rightarrow e \eta$

• For $\tau \rightarrow \mu \eta$, Neural network (NN) selection is also introduced.

Finally, the efficiency is higher than previous (around 1.5x on average), while similar background is achieved. ($\#BG < 1$)
Result for $\tau \to lP^0(=\pi^0, \eta, \eta')$

Belle preliminary

\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
$\tau \to$ & Eff. & $N_{BG}^{exp}$ & UL ($\times 10^{-8}$) & $\tau \to$ & Eff. & $N_{BG}^{exp}$ & UL ($\times 10^{-8}$) \\
\hline
$\mu\eta(\to \gamma\gamma)$ & 8.2\% & 0.63±0.37 & 3.6 & $\mu\eta'(\to \pi\pi\eta)$ & 8.1\% & 0.00±0.16-0.00 & 10.0 \\
$\mu\eta(\to \pi\pi\pi^0)$ & 6.9\% & 0.23±0.23 & 8.6 & $\mu\eta' \ (\to \rho^0\gamma)$ & 6.2\% & 0.59±0.41 & 6.6 \\
$\mu\eta(\text{comb.})$ & & 2.3 & & $\mu\eta'(\text{comb.})$ & & 3.8 \\
$e\eta(\to \gamma\gamma)$ & 7.0\% & 0.66±0.38 & 8.2 & $e\eta'(\to \pi\pi\eta)$ & 7.3\% & 0.63±0.45 & 9.4 \\
$e\eta(\to \pi\pi\pi^0)$ & 6.3\% & 0.69±0.40 & 8.1 & $e\eta'(\to \rho^0\gamma)$ & 7.5\% & 0.29±0.29 & 6.8 \\
$e\eta(\text{comb.})$ & & 4.4 & & $e\eta'(\text{comb.})$ & & 3.6 \\
$\mu\pi^0(\to \gamma\gamma)$ & 4.2\% & 0.64±0.32 & 2.7 & $e\pi^0(\to \gamma\gamma)$ & 4.7\% & 0.89±0.40 & 2.2 \\
\hline
\end{tabular}

→(2.1-4.4) times more stringent results than previous (401 fb$^{-1}$)
Detailed background study:
It turns out that not only 2photon process but also \(ee+X\) process become large background due to conversions.

\[\tau^-\rightarrow\mu^-\rho^0\text{ and }\tau^-\rightarrow\pi^-\pi^0\nu\text{ with }\gamma\text{ -conversion becomes }e^-K^*/K^*0\text{ backgrounds because }e/h(=\pi,K)\text{ separation is worse in low momentum region.}\]

\[B<(0.3-1.9)\times10^{-7}\text{ at }90\%\text{CL}\]

New search with 854fb\(^{-1}\) data sample

- Previous result
  Data: 543 fb\(^{-1}\) @ Belle, 451 fb\(^{-1}\)@BaBar
- Differently from \(\ell P^0\), 2photon process could be large backgrounds for \(\ell=e\).

Finally, higher or similar efficiency is kept (around 1.2x in average) while similar background level is achieved.
Result for $\ell V^0(=\rho^0, K^*, K^0, \omega, \phi)$

<table>
<thead>
<tr>
<th>$\tau\rightarrow$</th>
<th>Eff.</th>
<th>$N_{BG}^{exp}$</th>
<th>UL ($10^{-8}$)</th>
<th>$\tau\rightarrow$</th>
<th>Eff.</th>
<th>$N_{BG}^{exp}$</th>
<th>UL ($10^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e-\rho^0$</td>
<td>7.6%</td>
<td>0.29±0.15</td>
<td>1.8</td>
<td>$e-K^*$</td>
<td>4.4%</td>
<td>0.39±0.14</td>
<td>3.2</td>
</tr>
<tr>
<td>$\mu-\rho^0$</td>
<td>7.1%</td>
<td>1.48±0.35</td>
<td>1.2</td>
<td>$\mu-K^*$</td>
<td>3.4%</td>
<td>0.53±0.20</td>
<td>7.2</td>
</tr>
<tr>
<td>$e-\phi$</td>
<td>4.2%</td>
<td>0.47±0.19</td>
<td>3.1</td>
<td>$e-K^*$</td>
<td>4.4%</td>
<td>0.08±0.08</td>
<td>3.4</td>
</tr>
<tr>
<td>$\mu-\phi$</td>
<td>3.2%</td>
<td>0.06±0.06</td>
<td>8.4</td>
<td>$\mu-K^*$</td>
<td>3.6%</td>
<td>0.45±0.17</td>
<td>7.0</td>
</tr>
<tr>
<td>$e-\omega$</td>
<td>2.9%</td>
<td>0.30±0.14</td>
<td>4.8</td>
<td>$\mu-\omega$</td>
<td>2.4%</td>
<td>0.72±0.18</td>
<td>4.7</td>
</tr>
</tbody>
</table>

UL for $\tau\rightarrow\mu\rho^0$ is the most stringent among all the $\tau$-LFV decays.
Upper Limits on LFV $\tau$ Decay

At Spring on 2009
New Upper Limits on LFV $\tau$ Decay

Our sensitivity reaches $O(10^{-8})$! 100x more sensitive than CLEO's
LFV Sensitivity for future prospects

LFV sensitivity depends on background level

50ab⁻¹@next-generation B-factories is expected.

<table>
<thead>
<tr>
<th>Process</th>
<th>$N_{BG}@1ab⁻¹$</th>
<th>$N_{BG}@50ab⁻¹$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau\rightarrow\mu\gamma$</td>
<td>~7</td>
<td>~340</td>
</tr>
<tr>
<td>$\tau\rightarrow\mu\eta$</td>
<td>~0.7</td>
<td>~35</td>
</tr>
<tr>
<td>$\tau\rightarrow\mu\mu\mu$</td>
<td>~0.2</td>
<td>~8</td>
</tr>
</tbody>
</table>

Simple extrapolation

$\propto \frac{1}{\sqrt{\text{Lum.}}}$

$\propto \frac{1}{\text{Lum.}}$

---

Expected sensitivity

$\tau\rightarrow\mu\gamma$  $\text{Br}\sim \mathcal{O}(10^{-8-9})$

$\tau\rightarrow\mu\mu\mu, \mu\eta$  $\text{Br}\sim \mathcal{O}(10^{-9-10})$

To obtain improved sensitivity
- Better particle identification
- Better resolution for $\gamma$

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According to our study, main BG comes from $\tau \rightarrow \mu \nu \nu + \text{extra } \gamma$ (ISR or beam BG).

This can not be rejected by PID.

nobody knows how $\tau \rightarrow \mu \gamma$ behaves

1.5 ab$^{-1}$ generic $\tau \tau$ MC sample removed by MC generator info.

90% events removed!
Theoretical calc. for $\tau \to \mu \gamma$

• Most generic form for int. Lagrangian

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} \left\{ m_\tau A_R \tau \sigma^{\mu\nu} P_L \mu F_{\mu\nu} + m_\tau A_L \tau \sigma^{\mu\nu} P_R \mu F_{\mu\nu} + \text{H.c.} \right\},$$

Consequently,

- $A_L \neq 0, A_R = 0$ \quad $\mu$ in $\mu \gamma$ behaves similarly to $\pi$ in $\pi \nu$
- $A_L = 0, A_R \neq 0$ \quad $\mu$ in $\mu \gamma$ behaves oppositely to $\pi$ in $\pi \nu$

ex) SUSY SU(5) GUT

$$A_L \neq 0, A_R = 0$$

depends on

$$A_P \equiv \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}.$$
\[ \tau^- \rightarrow \pi^- \nu / \tau^+ \rightarrow \pi^+ \nu \]

\( \tau \)-rest frame

Hel. of \( \tau^- = 1 \)

Hel. of \( \tau^- = -1 \)
\( \tau^- \rightarrow \mu^- \nu \nu / \tau^+ \rightarrow \pi^+ \nu \)
\[ \tau^{-} \to \mu^{-} \gamma(L)/\tau^{+} \to \pi^{+} \nu \]

\( \tau \)-rest frame

\[ A_L \neq 0, A_R = 0 \]
\[ \tau^- \rightarrow \mu^- \gamma(R)/\tau^+ \rightarrow \pi^+ \nu \]

\( \text{hel. of } \tau^- = 1 \)

\( \text{hel. of } \tau^- = -1 \)

\( \cos \theta_{\tau^-} \text{ rest frame} \)

\( A_L = 0, A_R \neq 0 \)
BG rejection?

The region $0.0 < \cos\theta_+, 0.2 < \cos\theta_-$ is selected:

<table>
<thead>
<tr>
<th>mode</th>
<th>Remain(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu \gamma (L)$</td>
<td>41%</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \gamma (R)$</td>
<td>13%</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \nu \nu$</td>
<td>23%</td>
</tr>
</tbody>
</table>
Simulation with Belle 1 detector

- set beam (3.5/8 GeV) and detector as current ones
  - 1-1 topology + 1 $\gamma$ in signal side ($E_\gamma > 0.5$ GeV)
  - $\mu ID > 0.95$  $P_\mu > 0.6$ GeV/c
  - $1.5 < M_{\mu\gamma} < 2.0$, $-0.5 < \Delta E < 0.5$ (GeV)
  - When $\mu$ and $\gamma$ are decided, mother $\tau$ can be reconstructed. $\rightarrow$ $\tau$-direction

- helicity $\sim$ polar angle for $\tau$
  $\sim$ polar angle for $\mu$
  in CM frame.

$\cos \theta \tau^- > 0$
hel of $\tau^- = 1$
tau direction
from $\mu$ and $\gamma$, mother tau can be reconstructed and from it, another tau also can be reconstructed. (But, for BG, they are wrong information.)

$$\tau^{-}\rightarrow \mu^{-}\gamma(L)$$

$$\tau^{-}\rightarrow \mu^{-}\gamma(R)$$

$\pm$:

$$t^{-}g_{m}\pm \gamma(L)$$

$$t^{-}g_{m}\pm \gamma(R)$$

dot:

$$\tau^{-}\rightarrow \mu^{-}\nu\nu/\tau^{+}\rightarrow \pi^{+}\nu$$

$\cos\theta\mu > 0$

$\cos\theta\mu < 0$
Selection

\( \cos \theta_1 > 0, \cos \theta_2 > 0 \)

\[ \tau^- \rightarrow \mu^- \gamma (L) \]

\[ \tau^- \rightarrow \mu^- \gamma (R) \]

dot:

\[ \tau^- \rightarrow \mu^- \nu \nu / \tau^+ \rightarrow \pi^+ \nu \]

\( \cos \theta \mu > 0 \)

<table>
<thead>
<tr>
<th>mode</th>
<th>Remain(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \rightarrow \mu \gamma (L) )</td>
<td>38%</td>
</tr>
<tr>
<td>( \tau \rightarrow \mu \gamma (R) )</td>
<td>21%</td>
</tr>
<tr>
<td>( \tau \rightarrow \mu \nu \nu )</td>
<td>23%</td>
</tr>
</tbody>
</table>

\( \cos \theta \mu < 0 \)

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Summary

Lepton flavor violation is a good signature of NP.
We have updated search for $\tau$ LFV decays into $\ell+M^0(=\pi^0,\eta,\eta',\rho^0,K^{*0},K^{*0},\omega,\phi)$ and $\ell\ell\ell\ell$ using the world-largest data sample obtained by KEKB/Belle.

No LFV signals are observed yet and we set limits of branching fraction around $O(10^{-8})$.

→ Improve sensitivity by factor $\sim 100$ from CLEO
  • UL for $\tau\rightarrow\mu\rho^0$ is the most stringent among all the $\tau$-LFV decays
  • not only much larger data samples but also more effective BG rejection after detailed examination of the BG

In the future, SuperKEKB/SuperB projects will start with $\sim 50x$ higher luminosity.

→ BG will also increase proportionally to the luminosity.
  → $\tau\rightarrow\mu\gamma$ will have huge BG events.

Beam polarization will help to reduce BG.
  • L/R-type MC sample is considered. → hel. angle cut is sensitive to model.
  • checked with actual-setting data sample. → more realistic cut.

Belle started the analyses for the various modes using its full data sample!(~1ab$^{-1}$)
But, still, these figures for the angle of pi direction not to helicity but to tau direction.

When the angle between helicity direction and pi direction, one signature of cosine should be opposite. (Always, one tau direction corresponds to helicity direction while another direction is opposite to hel.)

To make them to the angle dist. to helicity.

After that, unify them, you obtain the dist for the angle to helicity.
Selection

$\cos \theta_1 < 0, \cos \theta_2 > 0$

\[ \tau^- \rightarrow \mu^- \gamma (L) \]

$\cos \theta_1 > 0, \cos \theta_2 < 0$

\[ \tau^- \rightarrow \mu^- \gamma (R) \]

$\cos \theta \mu > 0$

\[
\begin{array}{c|c}
\text{mode} & \text{Remain(\%)} \\
\hline
\tau \rightarrow \mu \gamma (L) & 23 \% \\
\tau \rightarrow \mu \gamma (R) & 41 \% \\
\tau \rightarrow \mu \nu \nu & 40 \% \\
\end{array}
\]

$\cos \theta \mu < 0$
\[
\tau^- \rightarrow \mu^- \gamma(\text{general})/\tau^+ \rightarrow \pi^+ \nu
\]

\[\mathcal{L} = - \frac{4 G_F}{\sqrt{2}} \left\{ m_\tau \bar{A}_R \tau \sigma^{\mu \nu} P_L \mu F_{\mu \nu} + m_\tau \bar{A}_L \tau \sigma^{\mu \nu} P_R \mu F_{\mu \nu} + \text{H.c.} \right\},\]

\[A_P = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}.
\]

\[
d\sigma(e^+ e^- \rightarrow \tau^+ \tau^- \rightarrow \mu^+ \gamma + \pi^- \nu) = \sigma(e^+ e^- \rightarrow \tau^+ \tau^-) B(\tau^+ \rightarrow \mu^+ \gamma) B(\tau^- \rightarrow \pi^- \nu)
\]

\[
\times \frac{s}{s - 4m^2_\tau} \frac{dz_\mu dz_\pi}{dz_\nu} \left( 1 - \frac{s(s-2m^2_\tau)}{(s-4m^2_\tau)(s+2m^2_\tau)} \right) \times A_P(2z_\mu - 1)(2z_\pi - 1), \quad (43)
\]